# Development of Traffic Control and Queue Management Procedures for Oversaturated Arterials

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The formulation and solution of a new algorithm for queue management and coordination of traffic signals along oversaturated arterials are presented. Existing traffic-control and signal-coordination algorithms deal only with undersaturated steady-state traffic flow conditions. No practical algorithms are readily available for oversaturated flow conditions. The main idea of the procedure is to manage queue formation and dissipation on system links so that traffic flow is maximized by efficiently using all green time, preventing formation of de facto red, accounting for the non-steady-state conditions, and providing time-dependent control measures. The problem is formulated as a throughput maximization problem subject to state and control variables. The solution is then obtained using genetic algorithms. The results show that the control procedure can produce dynamic and responsive control so that traffic progression is attained and all undesirable conditions such as queue spill-back and de facto red are avoided.

Traffic congestion is a daily occurrence in most urban areas in the United States. During these conditions efficient traffic management and signal control are critical determinants of the quality of operations of arterial systems. As such, appropriate tools for signal control and queue management in oversaturated traffic conditions are needed. Oversaturation is defined as a severe case of congestion in which vehicle queues along signalized arterials grow until they impede traffic operations at upstream intersections. Oversaturation may last for a limited time, but its aftereffects usually take a disproportionately long time to clear. The need for effective traffic control on oversaturated arterials becomes even more pressing with the deployment of more efficient traffic management schemes in intelligent transportation systems (ITS).

A new procedure is presented for signal control on oversaturated arterials based on queue management and efficient green-time use concepts. The main idea is to manage queue formation and dissipation on system links to maximize traffic flow by maximizing the use of green time, preventing formation of de facto red, accounting for the non-steady-state conditions, and providing time-dependent control measures. The problem is formulated as a throughput maximization problem subject to state and control variables. The solution to the problem is then obtained using genetic algorithms (GAs), an artificial intelligence technique.

## BACKGROUND

Early attention to signal control in oversaturated conditions was reported by Gazis (1), who proposed a way (using graphic methods)

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to control two closely spaced and oversaturated intersections. This procedure, however, is of limited use unless there are explicit constraints on queue length. Longley (2) presented a procedure for control of congested computer-controlled networks. The basic premise of Longley's procedure is to manage queues so that a minimum number of secondary junctions are blocked. Singh and Tamura (3) used the dual function of a delay minimization function to obtain a two-level hierarchical optimization strategy to control congested intersections. The control procedure presented was of the preventive type where constraints were used to control formation of queues. Michalopoulos and Stephanopoulos (4,5) used the optimal control theory to devise a control procedure that minimized delay of a system of oversaturated intersections subject to queue-length constraints. As it turned out, the solution to the problem may or may not exist if there is more than one constraint per intersection, and the optimal control becomes quite complex and impossible if pretimed signals are used. Vaughan and Hurdle (6) presented a theory for traffic flow for congested conditions in which the impact of origin-destination patterns on traffic dynamics and vice versa were explicitly modeled. However, the theory does not apply if congested intersections are close together. Shibata and Yamamoto (7) presented a methodology for control of congested urban road networks. This procedure, however, does not apply for closely spaced intersections where queue interference is present. Gal-Tzur et al. (8) presented a control method based on metering traffic to the capacity of the critical intersection (the one to become congested first) and then used TRANSYT-7F (9) to design a coordination plan. This procedure may be useful only in limited situations. Hadi and Wallace (10) reported on forthcoming enhancements to TRANSYT-7F to enable the program to analyze and optimize signal-timing plans under congested conditions. No specifics were given. Rathi (11) presented a control scheme based on avoidance of cross-street traffic spill-over. The scheme is applicable for recurrent congestion in steady-state flow conditions. Quinn (12) summarized strategies for congested networks.

None of these methods, however, is capable of dealing effectively with oversaturated conditions. Oversaturated conditions are characterized by lack of steady-state flow conditions and by significant interaction among traffic. Hence, during this type of condition, time-dependent and dynamic control of traffic signals becomes necessary to deal with traffic conditions as they emerge. The procedure proposed in this paper can provide this type of control.

The procedure is based on the algorithm presented by Abu-Lebdeh and Benekohal (13). It is different from previous procedures in many respects. It is dynamic, and the formulation of the problem accounts for the important aspects of the dynamics and time-dependent nature of traffic flow in oversaturated conditions. Several researchers (14,15) have noted the importance of accounting for the operational effects of these factors in oversaturated conditions.

GAs were used to solve the problem. This approach's adaptive, robust, directed random (but not exhaustive) search and flexible form of the objective function make it an ideal solution technique for dynamic control problems, particularly given the combinatorial explosion often associated with this class of problems.

## MOTIVATION FOR STUDY

At least two primary reasons account for the lack of control procedures for oversaturated conditions. First, traffic flow characteristics in a coordinated signal system are more complex than those in isolated intersections (*16,17*). Second, in oversaturated conditions, the problem becomes even more complex as traffic interaction increases and the steady-state conditions disappear. These two factors together make coordinated signal-system control in oversaturated conditions a complex task.

Notwithstanding these complexities, traffic engineers still need appropriate tools to coordinate signals in oversaturated conditions. Because such tools are not available, the engineer may inappropriately use currently available signal-coordination software such as PASSER II-90 (*18*) or TRANSYT-7F. These and similar software are intended for undersaturated conditions and as such they are not appropriate to oversaturated conditions. The results obtained from such inappropriate use can be misleading and may lead to inefficient traffic operation and prolonged congestion.

To illustrate what happens when this software is used inappropriately to design signal control in oversaturated arterials, conditions were created to simulate oversaturation. Demand at the boundaries of the system was made continuous and high enough to exceed the capacity of the system links. The two popular signal optimization and coordination programs, PASSER-II and TRANSYT-7F, then were used to optimize signal settings for a four-intersection arterial.

In oversaturated conditions with long queues, the two models do not correctly consider the queue length. TRANSYT-7F assumes that vehicles are stacked vertically (i.e., there is no queue length). For PASSER-II the user must specify the number of cars in the queue at the beginning of each cycle, and that amount cannot be more than five cars. Plots of offsets versus queue length for one of the arterial links (Figure 1) show that the offsets are the same regardless of the queue

length. This is counterintuitive because when the queue length on the receiving lane is longer, the offset for the upstream traffic should be longer. As a result, the two programs may report receiving more cars for a given link than what the link can handle physically. Intuitive reasoning indicates that a more realistic trend (not necessarily value) of offsets would be like those labeled "queue-based" in Figure 1. The queue-based offsets were estimated on the basis of typical assumptions of speed, acceleration rates, and discharge headways for given queue lengths.

Furthermore, for oversaturated conditions, when a queue does not clear completely and vehicles are left behind at the end of the green, these vehicles should be included automatically in the subsequent cycle. This process should apply for the entire control period. More important, the operational effects of carrying over vehicles and adding them to subsequent cycles should be accounted for. However, neither program does that. Instead, both TRANSYT-7F and PASSER-II optimize one condition and assume the rest of the control period to be a repetition of this condition. This assumption is reasonable in cases of undersaturated flow. In oversaturated conditions, each cycle is different. Furthermore, each cycle has some bearing on the cycles that follow. It is this dynamism that these and similar programs do not correctly consider, which makes their use in oversaturated flow conditions inappropriate.

This is not a criticism of PASSER-II or TRANSYT-7F because neither program is intended for application in this type of traffic condition. The point, rather, is to illustrate that inappropriate use of these otherwise useful programs may lead to erroneous conclusions.

Therefore, signal-coordination procedures that are appropriate for oversaturated conditions are needed. Specifically, such procedures should explicitly account for the operational effects of queues.

## FORMULATION OF CONTROL PROCEDURE

### Characteristics of Flow in Oversaturated Conditions

In formulating the control procedure for oversaturated intersections, it is essential to consider the relevant traffic phenomena that take place during oversaturation. When oversaturation prevails, one or more of the following interdependent conditions is encountered:

1. Flow conditions are not steady-state. Because more traffic is demanding service than can be accommodated, conditions during any time window are a function not only of traffic arrival and departure and signal control, but also of conditions during previous time windows. Hence, when controlling traffic during any cycle, the control scheme should account for conditions during previous cycles as well as conditions during the current cycle. This is a critical consideration that dictates that signal control become dynamic and time-dependent. In this case the problem is much more complicated than steady-state conditions in which one cycle is optimized and then applied for the entire study period.

2. Queue build-up. When green times for some approaches are not sufficient to process traffic demand, queue build-up forces upstream departure headways to increase because of hesitation by motorists, which may reduce capacity (*14,15,19*) and further propagate this effect to more intersections upstream.

3. De facto red. Extreme cases of queue build-up lead to complete blockage of upstream signals, where no traffic can discharge on a green signal. This condition is referred to in this paper as de facto red.
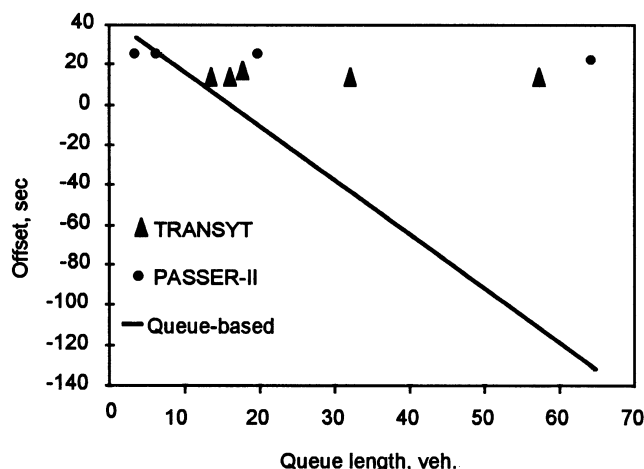


**FIGURE 1    Variation of offsets with queue length.**

A control procedure for oversaturated conditions must account for these traffic conditions.

## Optimization Criteria

During undersaturated flow conditions, successive signals are coordinated to provide a through green band so that traffic arriving from upstream signals goes through downstream intersections without having to stop. In this case the objective (criterion) of the control procedure is to minimize some disutility measure such as delay or number of stops. In oversaturated conditions, however, the concerns and overriding goals are different. Specifically, in oversaturated conditions a more appropriate objective would be to maximize the system throughput (*20*).

## Formulation

The proposed control procedure explicitly accounts for the conditions noted above and sets the control parameters to maximize system throughput. The procedure achieves this by ensuring that no green time is wasted and that all green time is used to the greatest (and most practical) extent possible. In addition, it ensures that when queues build up, they do not block the respective upstream intersections and ensures that de facto red is avoided. Through appropriate state equations, the control procedure ensures time-dependent, dynamic control. The control procedure is proactive; it attempts to influence traffic entering the system and then provides control so that undesirable conditions do not develop.

Although avoiding de facto red and not wasting green may appear as one class of actions, they are not. De facto red entails lost green time because traffic is not moving, whereas wasted green refers to green time that is not fully used although traffic is moving. De facto red may or may not lead to blockage of the intersection, depending on driver behavior.

In summary, the essence of the control procedure proposed here is to maximize system throughput while (*a*) ensuring using of all green time efficiently (no wasted green); (*b*) preventing formation of de facto red at intersections in the system; and (*c*) accounting for the non-steady-state system and providing time-dependent control measures. Conditions 1 and 2 ensure that no system capacity is lost and Condition 3 updates traffic conditions continuously (i.e., every cycle) so that control parameters are generated to respond to actual, not assumed, conditions. Mathematical expressions for these conditions are derived next. Lost time and transition (yellow) phases are not considered in the formulation at this point; however both can be incorporated easily.

Consider the three-intersection system shown in Figure 2 and refer to traffic flowing from Approach/Link 1 to Approach/Link 2. The following definitions are used:

$n$ = number of lanes on a given approach;

$s_i$ = adjusted saturation flow rate per lane of Approach $i$, veh/sec;

$S_i$ = adjusted saturation flow rate for Approach $i$, veh/sec, ($S_i = ns_i$);

$LV$ = average effective vehicle length when stopped, ft/veh;

$L_i$ = length of Link $i$, ft;

$l_{(k)i}$ = storage on receiving Link $i$ at the beginning of Cycle $k$, ft;

$t_{(k)i+1}$ = time for acceleration wave to reach tail of queue when signal turns green for Approach $i + 1$ at the start of Cycle $k$, sec;

$t_{si+1}$ = time for stopping wave to reach tail of queue when signal turns red for Approach $i + 1$ when Link $i + 1$ is full, sec;

$t_{q(k)i,\,i+1}$ = time for Queue $i$ to join Queue $i + 1$;

$\upsilon$ = speed of acceleration wave (a shock wave), ft/sec;

$\lambda$ = speed of a stopping wave (a shock wave), ft/sec;

$Cyc_{(k)j}$ = length of Cycle $k$ at Intersection $j$, sec;

$g_{(k)i}$ = effective green time for Approach $i$ during Cycle $k$, sec;

$DV_{(k)i}$ = discharged vehicles from Approach $i$ during Cycle $k$, veh;

$AV_{(k)i}$ = arriving vehicles into Approach $i$ during Cycle $k$, veh;

$q_{(k)i}$ = length of queue on Approach $i$ at the beginning of Cycle $k$, veh;

$off_{(k)i,\,i+1}$ = relative offset between Approaches $i$ and $i + 1$ for Cycle $k$, sec;

$exoff_{(k)i,\,i+1}$ = extended (or system) offset between Intersections $i$ and $i + 1$ for Cycle $k$, sec; and

$d_{(k)i}$ = mean departure rate from Approach $i$ during Cycle $k$, veh/sec.

The following subsections present the mathematical formulation of the previously mentioned three conditions.
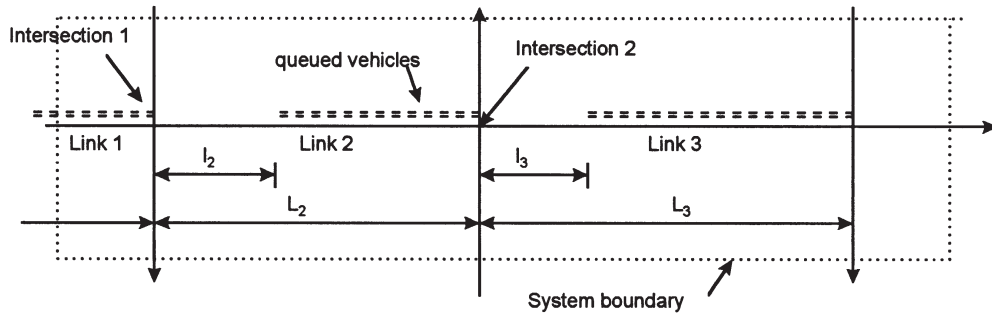


**FIGURE 2   Notation for link and intersection numbering.**

*Using Green Time Efficiently*

For efficient use of green time two interrelated conditions must be satisfied: Use of green time must be maximized, and this must be done at the maximum practical traffic-flow rate. To achieve the first, offsets should be set so that the first vehicle released from Approach 1 reaches the tail of the queue on Link 2, $q_2$, as the tail of $q_2$ has reached the desired speed (or the speed limit).

The time required for the tail of $q_2$ to start moving, $t_{(k)2}$, is determined by using shock-wave concepts. For Cycle $k$, when the signal for Approach 2 turns green, an acceleration wave ensues and reaches the tail of the queue in $t_{(k)2}$ sec, where $t_{(k)2} = q_{(k)2} LV/\upsilon$ and $q_{(k)2}$ is the number of vehicles queued on Approach 2 at the beginning of Cycle $k$.

The time required for the front of $q_1$ to join the tail of $q_2$, $t_{q(k)1,2}$, as the tail has reached its desired speed is determined on the basis of the traffic acceleration rate and the terminal speed. This can be determined easily by using Newton's laws of motion.

Therefore, to use green time efficiently, the offset is set so that it is equal to the difference between the time the two queues join and the time it takes for the tail of the downstream queue to start moving. In mathematical terms this can be expressed as

$$\text{off}_{(k)1,2} = t_{q(k)1,2} - t_{(k)2} \tag{1}$$

Note that $\text{off}_{(k)1,2}$ can be positive, negative, or zero.

Using green time at a maximum rate means maintaining the traffic flow rate at or close to the saturation flow rate by the combined effect of setting offsets as discussed above and by allocating green time–based traffic demand. Traffic demand at each link is determined dynamically (and updated) each cycle through the state equations (by keeping track of the number of vehicles discharging from and arriving at each approach).

*Preventing De Facto Red*

De facto red occurs when the signal indication is green but traffic cannot proceed because of backed-up traffic on the receiving link. To guard against this condition, green time for the upstream approach should be set with the knowledge of the length of the green time for the downstream approach, the offset between the two intersections, and the time it takes for a stopping shock wave to propagate upstream on a full link $L_2$ when the signal turns red for Approach 2.

On examination of the geometry of the time-space diagram in Figure 3, it is clear that avoiding de facto red for Approach 1 can be achieved if the following condition is satisfied:

$$[g_{(k)2} + \text{off}_{(k)1,2} + t_{s2}] \geq g_{(k)1} \tag{2}$$

where $t_{s2} = L_2/\lambda$ and $g_{(k)i}$ is the green time for Approach $i$ during Cycle $k$.

*Accounting for Non-Steady-State Conditions and Providing Time-Dependent Control*

Because of the significant longitudinal interaction among traffic during oversaturated conditions, flow during a given period is influenced by conditions during preceding periods. Hence, a realistic control during this type of condition should explicitly account for this interaction. The proposed procedure achieves this by tracking the formation and dissipation of queues at different approaches in the system by using a group of state equations, one for each internal link. For example, a queue at the downstream approach at the beginning of Cycle $k + 1$ equals the queue at the same approach at the beginning of Cycle $k$ minus the traffic that departed the approach during Cycle $k$ plus the traffic that arrived during the same cycle. For Approach 2 in this example, the general state equation is

$$q_{(k+1)2} = q_{(k)2} - DV_{(k)2} + AV_{(k)2} \tag{3}$$

where $q_{(k)i}$ is the number of vehicles in the queue at Approach $i$ at the beginning of Cycle $k$ ($q_{(k)i}$ is known from the previous cycle or given if $k = 1$); $DV_{(k)i}$ is the number of vehicles that departed from Approach $i$ during Cycle $k$; and $AV_{(k)i}$ is the number of vehicles that arrived at Approach $i$ during Cycle $k$. However, the traffic that arrived during Cycle $k$ at the downstream approach (Approach 2) equals the traffic that departed the upstream approach during the same cycle in which turning movements are not accounted for, that is,
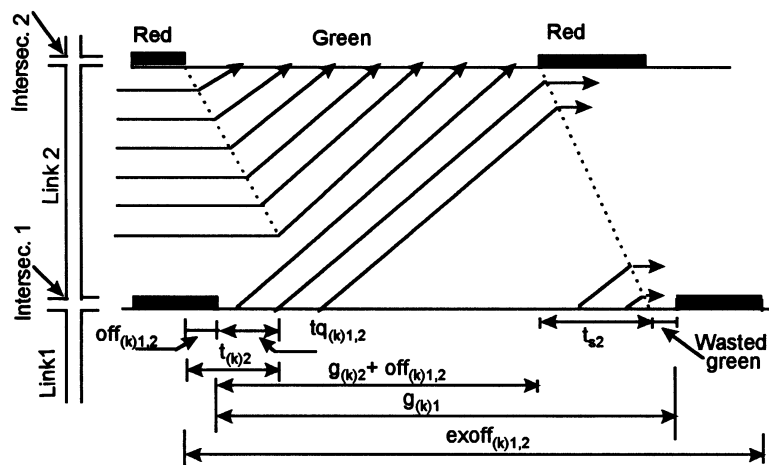
$$AV_{(k)2} = DV_{(k)1} \tag{4}$$



**FIGURE 3** **Relationship between signal timing and traffic flow of adjacent intersections.**

The state equations play two important roles. First, they functionally connect all internal links so they act as one system. Second, for a given link, they provide a mechanism for relating conditions of one cycle to conditions in the previous cycle.

Next, $DV_{(k)1}$ and $DV_{(k)2}$ are determined as functions of the respective green time and storage available on receiving links.

### Modeling Signalized Link Traffic Departures in Oversaturated Conditions

For a given Cycle $k$, traffic that departs Approach 2 depends on $g_{(k)2}$, $s_2$, $q_2$, and $AV_{(k)2}$. Depending on whether all green time is used at the upstream approach, the volume of departures from the upstream link (Link 1 in the example), $DV_{(k)2}$, is determined by the following equation:

$$DV_{(k)2} = \min\left\{\left[q_{(k)2} + \frac{AV_{(k)2}}{g_{(k)1}} \times \left(g_{(k)2} - \frac{q_{(k)2}}{s_2}\right), AV_{(k)2} + q_{(k)2}\right]\right\} \quad (5)$$

Ideally, $g_{(k)1} = [g_{(k)2} - (q_{(k)2}/s_2)]$, in which case Equation 5 reduces to

$$DV_{(k)2} = AV_{(k)2} + q_{(k)2}$$

In this case all green time at the upstream intersection ($g_{(k)1}$ in this case) is used and no queue is left behind on Link 2. However, conditions may dictate that some surplus green time be provided or that not all vehicles depart the downstream link (Link 2 in this case). Therefore, Equation 5 is used in the control algorithm.

In effect, the role of Equations 3 and 5 is to keep track of the evolution of queues on Link 2. This information is to be used in setting the control parameters in subsequent cycles. Similar equations may be derived for all internal links.

### Extended Offset

The role of the extended offset is to link relative offsets between each two intersections (given in Equation 1) to the functioning of the entire system over subsequent cycles. Figure 3 illustrates the relationship between signal timing and traffic flow of adjacent intersections, as follows:

$$\text{exoff}_{(k)i,i+1} = \text{Cyc}_{(k)i+1} - \text{off}_{(k+1)i,i+1}$$

where $\text{Cyc}_{(k)i+1}$ is the cycle length of the downstream intersection of the given pair of intersections.

### Constraints on Queues and Need for Flexible Cycle Length

If the conditions of efficient use of green and no de facto red (i.e., no lost capacity) are to be satisfied at all intersections, the length of green for both arterial and side approaches must be flexible, that is, its length may vary between cycles. This in turn dictates that cycle length be changeable at each intersection. However, if the cycle length is to be fixed, then explicit constraints must be placed on the lengths of queues on each system link. In this case system capacity loss may become inevitable, in which case a modified form of control must be formulated. This case is not covered in this paper, the focus of which is the case of minimum system-capacity loss and changeable cycle length.

### Other Important Considerations

The relationships presented earlier make up the main mechanism for achieving the stated goals. However, other conditions and constraints must be satisfied for the procedure to work. Most notable among these are the limits on cycle length and the minimum green times for crossing streets. In addition, the law of conservation of vehicles must hold.

## CONTROL ALGORITHM

For a system of $j$ intersections and $m$ cross-street approaches ($m = 2j$ if all cross streets are two-way), and for a study period of $n$ cycles, the optimal traffic control formulation to determine the optimal green times and the corresponding offsets is as follows: Find the trajectories of control variables (offsets, $\text{off}_{(k)i,i+1}$, and green times, $g_{(k)i}$) that maximize the objective function

$$\left\{\sum_{k=1}^{n}\sum_{i=1}^{n} g_{(k)i}\, d_i + j \right.$$
$$\left. \times \sum_{k=1}^{n} \min\left[q_{(k)j} + \frac{AV_{(k)j}}{g_{(k)j-1}} \times \left(g_{(k)j} - \frac{q_{(k)j}}{s_j}\right), AV_{(k)j} + q_{(k)j}\right]\right\} + \bar{\omega} + \omega$$

The first term of the objective function measures the throughput of the crossing streets. The second term is the throughput of the arterial street as measured by the number of link vehicles. $\bar{\omega}$ and $\omega$ are to adjust the throughput for the vehicles that did not travel all system links. A vehicle is considered to have traveled a link only after it has exited that link.

The above objective function is maximized subject to the constraints on the following control and state variables (Figure 3 presents the formulation of Constraints 2–4):

1. $DV_{(k)i} \leq q_{(k)i} + DV_{(k)i-1}$     $i = 1, \ldots, j; k = 1, \ldots, n$
2. $\text{off}_{(k)i,i+1} = t_{q(k)i,i+1} - t_{(k)i+1}$     $i = 1, \ldots, j-1; k = 1, \ldots, n$

$$t_{(k)_{i+1}} = \frac{LV q_{(k)i+1}}{\upsilon}$$

3. $\text{exoff}_{(k)i,i+1} = \text{Cyc}_{(k)i+1} - \text{off}_{(k+1)i,i+1}$
    $i = 1, \ldots, j-1; k = 1, \ldots, n$

4. $(g_{(k)i+1} + \text{off}_{(k)i,i+1} + t_{s\,i+1}) \geq g_{(k)i}$
    $i = 1, \ldots, j-1; k = 1, \ldots, n$

$$t_{s i+1} = \frac{L_{i+1}}{\lambda}$$

5. $q_{(k+1)i} = q_{(k)i} - DV_{(k)i} + DV_{(k)i-1}$     $i = 1, \ldots, j;$    $k = 1, \ldots, n$

$$DV_{(k)i} = \min\left[q_{(k)i} + \frac{AV_{(k)i}}{g_{(k)i-1}} \times \left(g_{(k)i} - \frac{q_{(k)j}}{s_i}\right), AV_{(k)i} + q_{(k)i}\right]$$
$$i = 1, \ldots, j; \quad k = 1, \ldots, n$$

6. $\bar{\omega} = - \sum_{i=2}^{i} q_{(1)i} \times (i - 1)$

7. $\omega = \sum_{i=2}^{i} q_{(n+1)i} \times (i - 1)$

8. $g_{(k)i} \leq$ maximum value     $i = 1, \ldots, j;$    $k = 1, \ldots, n$
9. $g_{(k)i} \leq$ maximum value     $i = m - 1, m;$    $k = 1, \ldots, n$
10. $q_{(1)i}$ are given     $i = 1, \ldots, j$

### Control Algorithm Solution

The problem presented is a typical dynamic discrete-event problem. Classical solution techniques such as dynamic programming and the

maximum principle may be used to solve such a problem provided specific criteria are satisfied. A more recent and superior solution technique is GAs. GAs were used to solve this problem because of their ability to deal with large and combinatorial problems and because of the flexibility they allow in formulating the objective function.

GAs are robust optimization and search techniques based on the mechanics of natural selection and natural genetics (*21*). Although such mechanics are simple, they are quite powerful. As in all artificial intelligence techniques, a key feature of GAs is that they provide an appropriate and efficient method to represent knowledge in the computer and to get real-world knowledge into an internal or machine representation. Put simply, a GA works by generating an initial pool of solutions, represented as string structures, and then through continuous and systematic copying, swapping, and modifying of partial strings in a manner that mimics natural genetic evolution, the GA allows the solution pool to evolve toward improved solutions.

### *GAs in Transportation*

GAs have been applied successfully to traffic and transportation problems, although their use in this field is still limited. Foy et al. (*22*) reported on using GAs to determine signal settings. Hadi and Wallace (*23*) used GAs to obtain optimal phasing for signal coordination. Fwa et al. (*24*) and Chan et al. (*25*) used GAs in the combinatorial problem of optimizing pavement maintenance. Memon and Bullen (*26*) compared GAs to the quasi-Newton gradient method and chose GAs for real-time optimization of signals.

The main aspect of GAs that made them attractive for use in this problem is their ability to overcome the combinatorial explosion of problems like the one at hand. The magnitude of the problem can be demonstrated easily by the following example. Consider a system of $j$ intersections, a study period of $n$ cycles, and a range of green time of $y$ seconds for arterial approaches and $z$ seconds for the key (or critical) side-street approach. Assume that each intersection has two phases and that the search for optimal green times is to be done in $s$-second steps. On the basis of the formulation of the problem, there would be $n(j + 1)$ control variables, and hence $(y/s)^{nj} \times (z/s)^n$ possible solutions. For a modest system having $j = 5$ intersections, $n = 10$ cycles, $y = 50$ sec, $z = 20$ sec, and $s = 5$ sec, there would be a total of $1.05 \times 10^{56}$ solutions. This number would be gigantic with larger systems and longer control periods. It would take a computer an extremely long time to evaluate all of these solutions. An intelligent search such as that used in GAs can avoid nonoptimal regions and learn from past knowledge, thus reaching a near-optimal solution in remarkably less time. This has direct implication for on-line control. Furthermore, traditional mathematical programming may not reveal multiple optimal (or near-optimal) solutions. In situations like this, GAs were found to provide acceptable solutions within a practical period (*21*).

### *Using GAs for This Case*

The control algorithm was applied to a five-intersection system with the same timing parameters noted earlier. Traffic flow was assumed to be one way and turns were ignored. The results presented in the following section were obtained on the basis of the following geometric and traffic input: $L_1 = 243.8$ m (800 ft), $L_{2\ldots5} = 304.8$ m (1,000 ft), $q_{(1)1} = 20$ vehicles, $q_{(1)2\ldots5} = 15$ vehicles, $LV = 7.62$ m (25 ft),

$\lambda = 4.26$ m/sec (14 ft/sec), $\upsilon = 4.9$ m/sec (16 ft/sec), $s_i = 1,800$ vehicles per hour (vph) for all $k$, and $i = 1, \ldots, 5$. A mean arrival rate for cross approaches of 1,260 vph was used.

## RESULTS

### GA Solution

To ensure unbiased results (i.e., results not dependent on the starting point), runs of the algorithm were executed each starting with a different random seed number. All runs converged to about the same objective function value; however, the resulting control trajectories were different in each run. This is an indication that the problem has multiple optimal or near-optimal solutions. Nonetheless, all trajectories were of comparable overall quality. The results presented next are from one selected run.

The run was executed using a micro GA. A micro GA takes a small population, $n$ for example, converges it, keeps the best individual, randomly generates $n - 1$ individuals, converges the new population, and so on. The run was executed for 4,000 generations with a population of five. This means that the fitness function was executed 20,000 times. At each generation, the average fitness of the generation is calculated and the member in the population with the best fitness value (i.e., the highest link-vehicles) is identified. Figure 4 illustrates how the GA starts with a low system throughput and locates good individuals in later generations. It is noted that most improvements in the objective function occurred in the first 400 generations, with a slower improvement rate observed thereafter. Hence, for practical considerations one may terminate the runs at the 400 generation without much loss in the objective function value. In this case, the number of fitness function evaluations will be cut to 2,000.

### Allocation of Green Time

Figure 5 illustrates how arterial and side-street green times were changing over the study period. Note how, for a given cycle, the green time for the arterial approaches increases in the downstream direction. Not only is this desirable, but it is what one should hope for in conditions of oversaturation and long queues. This pattern is exactly what is required to clear queues from within the system links (starting with downstream queues, of course) before normal forward progression begins. Note also that one other prerequisite for progression has been achieved—the common cycle length. As in Figure 5, for later cycles, the allocation of green time between crossing and arterial approaches has changed over time in such a way that a common cycle length is maintained.

The preceding two observations are a clear demonstration of the capability of the algorithm to effectively handle oversaturated conditions, whereby it first managed and dispersed existing queues and then provided signal settings so that normal forward progression was achieved.

Figure 5 also shows that for certain cycles more green time is allocated to the side street than to the arterial. This may appear counterintuitive but it is not, because when a long queue is present in the downstream approach, only limited arterial traffic may be released from the upstream approach, which requires a short green time. If longer green is given, intersection blockage may occur. In such a case the algorithm allocates only limited green to the arterial, with the rest of the green given to the side street. Therefore, the apparent
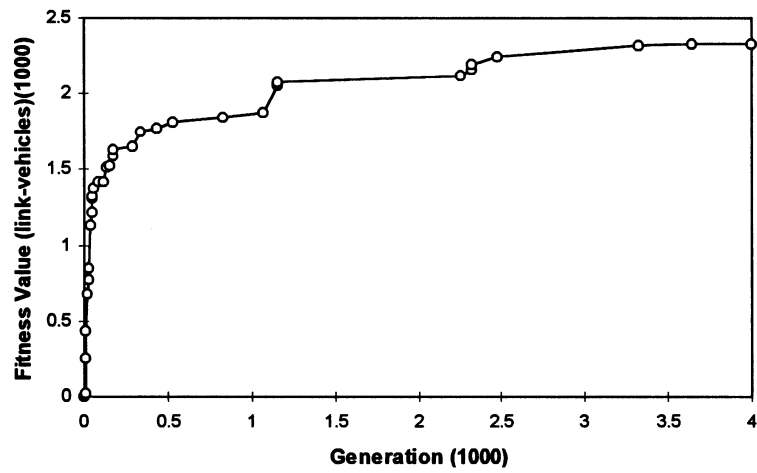
**FIGURE 4    Progress of GA control algorithm toward best solution.**
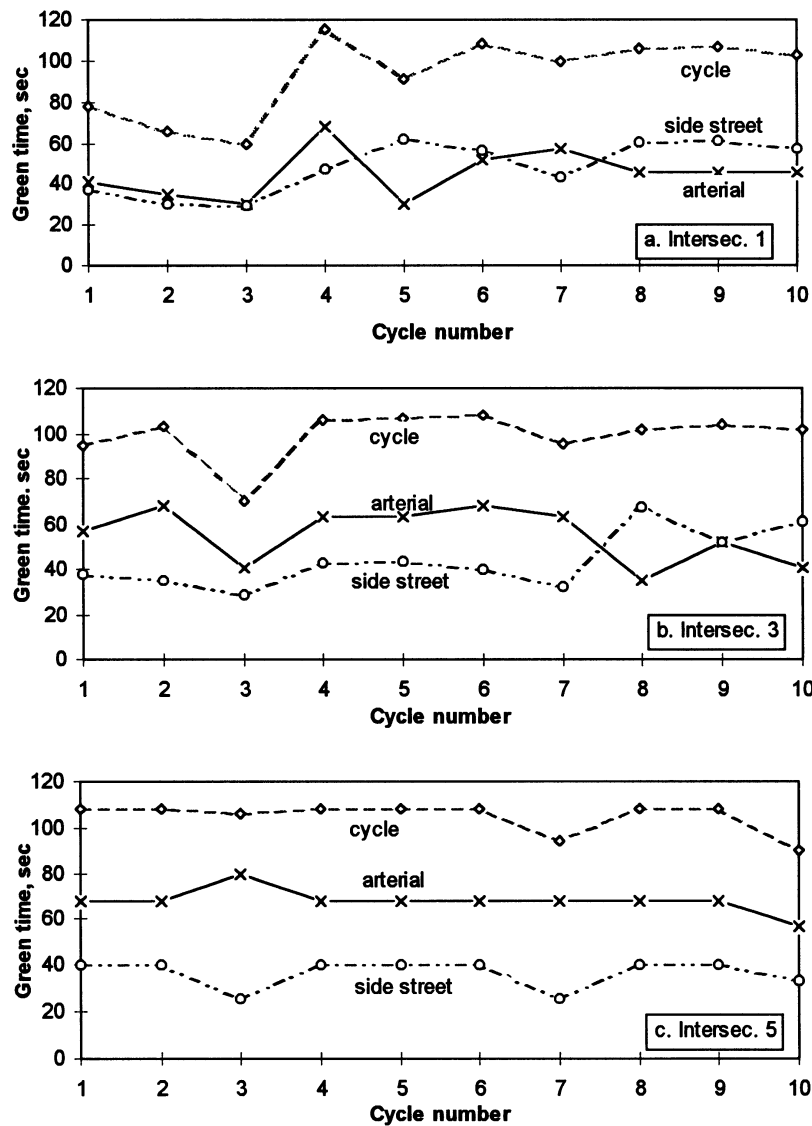


**FIGURE 5    Variation in green times for arterial side-street approaches over study period.**

counterintuitive allocation of green time actually is more the result of the algorithm's trying to avoid intersection blockage (hence de facto red) and to ensure efficient use of green time.

## Queues and Offsets

Figure 6 shows upstream intersection offsets as a function of queue lengths on downstream links. Since offsets were designed to respond to actual queues, a close association in the trends of both may be noted. In the early cycles, where significant queues are present, the offsets are observed to start with negative values (typical of queue clearance operations). As queues were being reduced, the offsets gradually were changing to higher positive values, which is typical of normal progression operations. These positive values fluctuated proportionately in response to the minor queues that reappeared on some of the links.

The cycle-to-cycle fluctuation of offsets is due to the number of vehicles in the queue at the downstream approach. Therefore, this pattern is more realistic and, hence, very desirable. It is an indication that the offsets are responding to actual traffic conditions. So, as

expected, the algorithm is responding to demand but with consideration of actual existing traffic. Hence, this fluctuation does not mean that the algorithm is unreasonably changing the offsets between cycles. For example, note that if the queue remains the same, the offset does not change. Also, when the queues are cleared, the offset fluctuations diminish (or disappear altogether), which is exactly what should normally be expected (Figure 6).

## CONCLUSIONS AND RECOMMENDATIONS

This paper presents the formulation and solution of a new algorithm for queue management and coordination of traffic signals along oversaturated arterials. The proposed algorithm is different from existing coordination procedures in two important respects: It is dynamic and time-dependent, and it explicitly recognizes the presence and operational effects of queues on receiving links. A solution using GAs was demonstrated for an example network composed of five signalized intersections. However, the algorithm may be used for any size system. Only practical considerations (such as computer memory, CPU time, etc.) may limit the size of a system.
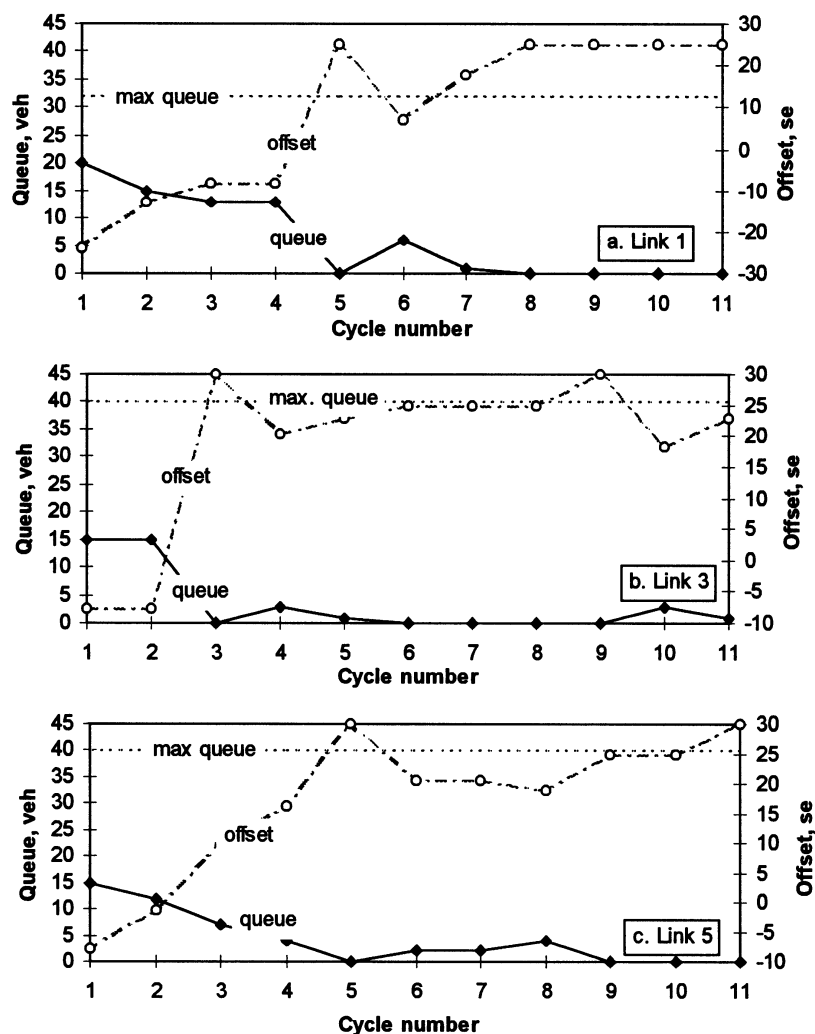


**FIGURE 6    Upstream intersection offset as a function of queue on downstream link over study period.**

The results show that the control algorithm can provide dynamic, time-dependent traffic control. Offsets and green times were dynamically changed as a function of demand and queue lengths. When long queues were present, the algorithm utilized appropriate (negative) offsets to reduce or eliminate these queues and then gradually moved into a positive offset-setting mode to provide forward green bands, hence normal traffic progression. These robust features are lacking in current coordination programs. Last, it should be noted that the algorithm has good potential for on-line real-time implementation in an ITS environment.

The results support the notion that signal coordination in oversaturated conditions should be dynamic and time-dependent and that offsets should be based on explicit consideration of queue lengths. Several improvements must be incorporated into the current formulation before the procedure is ready for real-life applications. Cases with turns and two-way traffic should be covered. The procedure should be tried on larger systems. Work is under way to address these points.

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